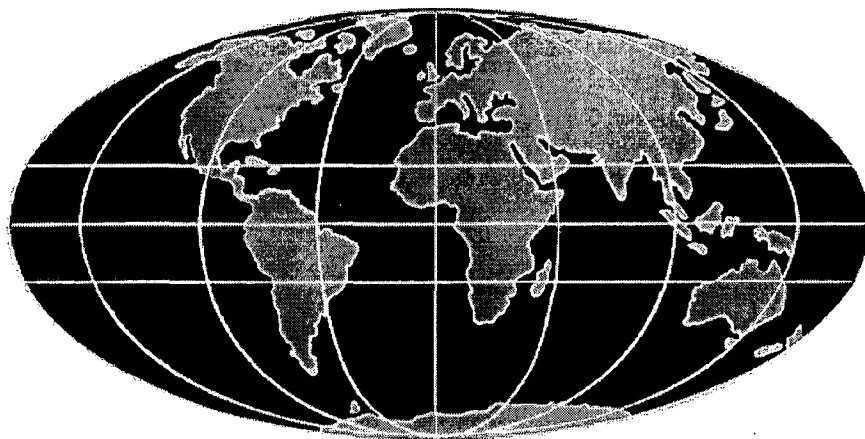# DFID
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TITLE: Expansive soils: TRL's research strategy

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EXPANSIVE SOILS: TRL'S RESEARCH STRATEGY

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ABSTRACT   This paper describes some aspects of a TRL programme of research on expansive soils.   The aim of the research programme was to provide practising engineers with guidance on design and construction of roads built on or with expansive soils.   Particular emphasis was placed on the development of improved identification procedures, both in the laboratory and in the field, for expansive soils.   A further aspect of work was the development of new techniques whereby the influence of suction on the soil behaviour could be investigated both in the field and the laboratory.   The influence of stress, density and moisture content on the swelling characteristics of compacted expansive soils was investigated experimentally using a range of swell test procedures. Recommendations were then made on appropriate test procedures for assessing the swell characteristics of compacted expansive soils. The practical application of the research programme is to provide road engineers with guidance on; laboratory and field identification of expansive soils, laboratory swell testing of expansive soils, assessment of the potential for volume change in the field and the options available for road design.

INTRODUCTION

Expansive soils are generally characterised by the presence of a clay mineral of the smectite group. These soils can give rise to problems in civil engineering works because of their capacity to undergo large volume changes with changes in the moisture content or suction.

Some examples of the annual cost of damage to buildings and light structures, including roads, caused by expansive soils are $1000 million in the USA, $150 million in the UK and at least $4 million in South Africa.   Expansive soils are found on all five continents and are especially widespread in the wet and dry tropics.   There are no statistics available for the cost of damage in these areas but it is clear that the figures given above represent only a small proportion of the cost of the problem worldwide.

The Transport Research Laboratory (TRL) has been involved in various aspects of research on these soils. This has involved collation of existing information and an extensive programme of laboratory research.   The laboratory research carried out with Imperial College London concentrated on methods for identification and evaluation of swell of expansive soils.   Particular reference was placed on their behaviour under conditions of partial saturation, where large negative pore water pressures can be present.

The aim of the research programme was improve the understanding of these soils as construction materials, clarify the design requirements for their use and to make this information available to

highway engineers. The overall strategy and outputs of the research programme is illustrated in Figure 1. The programme was structured to include information on:

(a)   identification and engineering significance of expansive soils,

(b)   potential for volume change in the field,

(c)   laboratory evaluation and geotechnical properties of expansive soils, and

(d)   use of expansive soils in road engineering

A series of reports will be published by TRL to describe each element of the work in more detail. .. Practical guidelines for highway engineers will be prepared encompassing each of the four elements given above. This paper briefly reviews some the main research findings from the study.

IDENTIFICATION AND ENGINEERING SIGNIFICANCE

Damage caused by expansive soils is almost entirely restricted to light structures and is a particular problem when they are encountered in road construction. Early identification during site investigation and laboratory testing is extremely important to ensure that the correct design strategy is adopted.

Expansiveness is a property of the soil. There is no direct measure of this property and therefore it is necessary to make use of comparative values of swell, measured under known conditions, in order to derive a method for assessing expansiveness. Consideration of the mechanisms of interaction between water and clay soils show that the three most important components are the clay minerals, the change in moisture content or suction and the applied stresses. The type of clay mineral is largely responsible for determining the soil property referred to as the intrinsic expansiveness. It is the change in moisture content or suction that controls the actual amount of swell which a particular soil will exhibit under a particular applied stress.

Identification of intrinsically expansive soils

It is important that geotechnical and materials engineers should have a reliable method available for identifying expansive soils. Many attempts have been made in the past to provide such a method by comparing swell data with one or more commonly determined soil index values. Each may have some validity for a particular set of soils and conditions but none has proved universally reliable. Reasons for the failures of past attempts to use index tests centres around the important influence of soil microfabric and stress history on the swelling characteristics.

A procedure has been developed as part of this study which avoids the problems inherent in the use of compacted or natural undisturbed samples and allows soils to be compared purely on the basis of expansiveness without interference from microfabric and stress history. The proposed means of estimating the intrinsic expansiveness is shown in Table 1 using the liquid limit (BS 1377, part 2, 1990) on the horizontal axis and the difference between the

plastic limit (BS 1377, part 2, 1990) and the shrinkage limit (ASTM D4943-89 (1992)) determined using the American procedure on the vertical axis. The lines on the graph, shown in Table 1, represent contours of expansiveness, (%), determined using:

$$\frac{(e_{15}-e_{SL})}{(1+e_{SL})}$$

where: e_{15} is the void ratio after swelling of samples reconstituted, consolidated and dried past the shrinkage limit before swelling in an oedometer under 15kPa vertical stress, and

e_{SL} is the void ratio determined at the shrinkage limit of the dried samples.

The soil is reconstituted by mixing to a paste at a moisture content of approximately 1.2 of the liquid limit. The paste is placed in an oedometer and consolidated in stages to 1000kPa. After unloading in stages to 100kPa, the sample is dried to the shrinkage limit and e_{SL} determined. The sample is then allowed to swell in the oedometer under 15kPa vertical stress until swelling is complete. The void ratio, e_{15}, is then determined at the end of this swelling stage.

The graph serves to provide comparative data for soils but does not provide a means of estimating expansiveness for any other conditions. Further data is being collected to validate the procedure.

POTENTIAL FOR VOLUME CHANGE OF EXPANSIVE SOILS

The occurrence of changes in the moisture conditions beneath covered areas has been extensively documented. This part of the research programme addressed those issues which are of importance in understanding the changes that are likely to occur beneath roads in various climatic regions. Surprisingly little useful data are available, although the general trends of changes are moderately well defined. The deficiency in reliable field suction data became apparent during this part of the study and a clear need was identified for development of suitable and simple methods for *in situ* and laboratory measurement of soil suction. A rational approach for the field and laboratory identification of expansive soils was developed which gives the engineer a strategy whereby expansive soils can be identified at an early stage in the site investigation.

Rational approach to identification of expansive soils

The engineering performance of a soil *in situ*, whether tropical or temperate, residual or transported, will depend on at least all of the following:

    a)   Mineralogy and composition (from index tests/grading),
    b)   Fabric and structure (from visual/microscopic study),
    c)   Stress history (from geology/laboratory tests), and
    d)   Applied stress changes (from design, construction and climate).

The composition, state of saturation and engineering properties of the soils provide valuable information for the engineer in the early stages of project planning and design. To satisfy this need the identification strategy incorporating the field assessment and laboratory test procedures shown in Table 1 is suggested. The identification process is divided into three sections. The first considers the information available through geological and geomorphological investigation. The second covers the procedures available for the assessment in the field by the engineer, where detailed soil profiling, assessment of the moisture condition and identification of soil class are the minimum requirement. The third section considers simple index tests which can be carried out in the laboratory to identify the intrinsic expansiveness of the soil.

Changes to *in situ* moisture and suction

Expansive soils become a particular problem where the prevailing climate is:

(a)   arid and the "dry" soils are subjected to unusually high rainfall, causing the soil to wet and expand,

(b)   semi-arid and the moisture condition of the soil reflects the wet-dry seasonal cycle.

(c)   predominantly wet and they are subjected to a prolonged period of drought and exhibit drying shrinkage,

To better assess the behaviour of the soil in the laboratory or field, due consideration should be given to the influence of climatic factors and the potential for the moisture content or suction of the soil to vary. Moisture conditions beneath the ground surface are described by the moisture content and the pore water pressure. Where the pore water pressure is negative, i.e. there is a water deficit in the soil, the pore water pressure is usually referred to as the suction.

Various factors will affect the moisture content and the suction of the soil and a change in one will be associated with or will cause a change in the other. Water can be supplied to the soil by rainfall, rising ground water level and by local phenomena such as, irrigation, leaking pipes etc. These increase the soil moisture and are associated with a decrease in suction toward a value of zero. Acting in opposition to this supply of water are those processes which act to extract water from the soil. These include, for example, evaporation, transpiration and the lowering of the groundwater level. These decrease the available soil moisture and are associated with an increase in the suction of the soil.

The equilibrium suction in compacted soils beneath sealed road surfaces has been related to the prevailing local climate by use of the Thornthwaite Moisture Index (TMI) by Russam and Coleman (1961). Regions with a TMI of -20 to -40 are considered semi-arid, with those showing values of TMI below -40 arid. This is illustrated in Figure 2 for a heavy clay material, such as expansive clay, where the data were obtained from samples taken at a depth of 45cm in road sub-grades. The sites where the data were collected had deep soil profiles and deep water tables. Different relationships were found between suction and TMI for different soil types. Figure 2 is assumed to be representative of the "equilibrium" conditions beneath

a sealed surface where the above conditions apply and there is good drainage, uniform vegetation (without trees) and no change in condition caused by infiltration.

Problems arise, particularly for the expansive soils group, where the local conditions modify the equilibrium suction from this reference line. Differential wetting can be caused in a road sub-grade by run-off from the sealed surface, lateral infiltration, leakage from culverts, fluctuation in the ground water table, and the influence of vegetation. In arid areas it may be the influence of these factors, rather than those of the ambient climatic regime, which dictate the volume change and consequent heave and shrinkage of expansive soils used in road construction.

Seasonal movement (alternating heave and shrinkage) can occur where alternate wet and dry seasons are a feature of the climate. Design and repair are more difficult where this wetting and drying regime exists. This form of alternating heave and shrinkage is generally accepted as the primary cause of longitudinal cracking in sealed roads over expansive soils (Dagg and Russam 1966).

Suction measurement

It is recognised that the determination of soil suction, although difficult in practice, can give a fundamental insight into the performance of the soil as an engineering material. In temperate (or wet climates), where the science of soil mechanics developed, there is generally an excess of rainfall over evaporation. Soils generally remain saturated and pore water pressures remain positive. For these conditions the effective stress theory was developed and can be expressed as:

effective stress = total stress - pore water pressure

The effective stress is the component which controls the behaviour of saturated soils. If the effective stress changes then the soil will undergo a volume change. For example, if the effective stress is increased then the volume will decrease and vice versa. It is also the effective stress that controls the strength of a saturated soil. Increasing the effective stress will increase the strength of the soil.

In dry climates there may be an excess of evaporation over rainfall, leading to a water deficit. This is seen in the form of a negative pore water pressure (or positive suction) and results from evaporation and vegetation removing water from the soil. If the negative pore water pressure is sufficiently large air enters the soil and the effective stress equation is no longer adequate. To describe the state of stress in the soil it becomes necessary to investigate soil behaviour in terms of total applied stress $(\sigma - u_a)$ and suction $(u_w - u_a)$. Changes in both total stress and suction will cause, separately, changes in volume and strength.

Since suction is one of the two stress variables which controls soil behaviour, we must be able to measure the suction in order to make progress in the understanding of road performance in non-temperate climates. As part of TRL's wider study of expansive soils, a suction probe was developed to measure suction in subgrade soils and

embankment fills under experimental road pavements constructed by TRL in developing countries. The system uses filter paper which acts as a disposable sensor sealed within an easily installed sensing chamber. Data are being collected from a range of field sites to allow the influence of suction on the behaviour of these soils to be evaluated. In the laboratory, measurement of suction in soils cannot routinely be made except for the very low range (0 to 100kPa) of suction. A comparative experimental study was undertaken to evaluate a range of laboratory suction measurement techniques, including filter paper, pressure plate and psychrometers in addition to pressure plate control tests. All the methods investigated were shown to be reliable and to give comparable results. The filter paper method was favoured as a routine measurement system because it is cheap, simple to use and could be used over a wide range of suction. Additionally, the filter paper had the advantage that it could be used for measurement of both matrix and total suction. The two measurement systems, both based on the filter paper technique, can be used in tandem for reliable measurement of soil suction.

LABORATORY EVALUATION OF EXPANSIVE SOILS

As part of the research programme, information has been compiled summarising the geotechnical properties of highly plastic or expansive soils. This has included laboratory test information from classification data, strength parameters, compaction characteristics and swell test data. Further laboratory tests were carried out to investigate the effect of stress and fabric on the engineering behaviour of the soil. These tests showed the importance of distinguishing between swelling of compacted, undisturbed and reconstituted samples. Compacted soils may have a microfabric that is very different from that of the undisturbed soil. This may in turn have a microfabric that differs from that in a sample of the same soil which has been reconstituted (i.e. consolidated from a moisture content above the liquid limit). The intrinsic expansiveness will not vary between these samples, but the microfabric present in the soil before wetting may have a significant modifying effect on the measured swell if the microfabric is susceptible to alteration.

Very few comprehensive suites of testing have been performed on expansive soils. The test suite required includes liquid and plastic limits, shrinkage limit, clay size fraction, the fraction passing the 425μm sieve (if so separated for index tests) and an appropriate swell test together with CBR, compaction or shear strength tests if desired. Very often some of the classification tests are omitted. It is common to find soils described as expansive without reference to any swell test or field heave data.

Laboratory testing of highly plastic or expansive soils can often be a problem. Those procedures where particular guidance will be of benefit have been summarised in Table 2. Some field investigation procedures are also considered which can provide reliable design data and avoid some of the problems associated with laboratory testing.

Index tests

Many correlations have been made between routinely determined soil properties, such as Atterberg Limits, and the magnitudes of swell obtained from case histories or measured in laboratory swell tests. Generally these are empirical relations which fail to distinguish between the three major components involved (expansiveness, suction change and applied stress). Attempts to correlate the Atterberg Limits, which should reflect the clay mineralogy and thus intrinsic expansiveness, with the observed swell cannot be made. The observed swell will reflect the particular moisture change and applied stress used in the test procedure. A limited degree of success has however been achieved with some of these methods.

The one situation where index data may be used on its own for the prediction of field behaviour is where the engineering processes obscure or destroy the effect of factors such as microfabric and previous stress history. This condition can arise where the soil is used for fill and road formations. The natural stress history, fabric and structure of the soil are replaced by those imposed during the engineering processes. Those factors remaining which dictate the engineering performance include the soil type, the design, construction and climatic factors.

Swell tests

Measurement of swell for design purposes should simulate the expected sequence and magnitude of loading and wetting changes that are expected in the field. The use of standard oedometer test procedures where the soils are soaked to zero suction were investigated as part of the study. These are "quick" tests which provide data on volume change and vertical stress only and have been used to investigate the influence of parameters such as vertical stress and compaction moisture content on swelling. The swell data obtained for a number of expansive soils, compacted at a range of initial moisture contents and allowed to swell under a range of vertical stress, was compared with Brackley's (1983) swell prediction equation. The results showed that although Brackley's equation gave similar patterns swelling, the values calculated can be so different that the equation must not be universally applied. For example, a sample of expansive clay from Kenya compacted at 6% moisture content and subjected to swelling under 64kPa vertical stress gave a measured swell of 92% with 115% swell predicted using Brackley's equation. For the same soil compacted at 35% moisture content, under a 1.5kPa vertical stress, the comparison was good, with 34% swell measured and predicted. However, for the same compaction moisture content and a vertical applied stress of 256kPa, 14% swell was predicted using Brackley's equation where no swell was measured.

Advanced evaluation of swell tests

In general, and particularly in arid regions where these soils are compacted at a moisture content close to the optimum moisture content, they do for the most part dry back and exhibit a negative pore water pressure. It is clear that information on the volume change at an applied vertical stress under soaking in the standard types of oedometer may not reflect the response of the soil *in situ*. TRL commissioned the design and fabrication of a hydraulic oedometer

for determination of the full stress state during swelling and compression of unsaturated soils, where the matrix suction can be measured or controlled.

Tests can be carried out in the stress path oedometer for detailed study of the volume change characteristics of compacted expansive soils under controlled suction and applied stress. The tests are "slow" in comparison with the standard oedometers but provide data on axial (vertical) and radial total stresses, suction and void ratio (or volume). The programme of tests carried out using the stress path oedometer allowed evaluation to be made of the swell measured in three standard oedometer procedures. Investigation of alteration of the microfabric during swell. and swell pressure testing was also carried out.

EXPANSIVE SOILS IN ROAD ENGINEERING

The design engineer needs to address the influence of expansive soils both as naturally occurring undisturbed soils beneath the road and as compacted soil in the road formation. It is therefore necessary to identify the source of expected heave or shrinkage before selecting the design solution. There may be little benefit importing non-expansive fill materials if the undisturbed soil beneath the road formation is expansive and heaves with consequent damage to the entire road structure. Those issues which are of importance in understanding the moisture changes that are likely to occur beneath roads in various climatic regions have been reviewed. Generally where a strength design is based on a permanently wet condition it is conservative or over-designed. No guidance has been found on the engineering implications of changes in moisture content or suction during the life of a road, nor on their effect on CBR values as determined in the laboratory. However, in areas with seasonal variations of moisture content and suction in the soil, damage in the form of longitudinal cracking can occur, whilst spatial variation of density, suction and soil type can cause differential heave.

For the road design engineer working in areas of expansive soils six options were identified which should be considered where both *in situ* and compacted expansive soils are present. These are:

    (a)   Alter the route/alignment to avoid the expansive soil.
    (b)   Remove the expansive soil and replace it with non-expansive material.
    (c)   Design for the low strength and allow for maintenance to repair heave deformations.
    (d)   Provide non-expansive material as a cover or surcharge layer.
    (e)   Control moisture movement.
    (f)   Improve the expansive soil by stabilisation.

The choice of which option or combination of options depends primarily on the size of the project, economic considerations and the element of risk acceptable to the client. It seems sensible to suggest and base judgement on the argument that if a method is effective in preventing damage then it is justifiable to use that method in preference to another which is seen as less reliable. Cost considerations, though important, should not totally dictate design.

Generally a compromise must be sought between quality, performance and cost. The selection of one design method over another must be made through reasoned engineering judgement and understanding of all those factors which can affect change and should not be based solely on short term cost considerations. It is also important to note that though there is an apparent increased cost of using a preventative design approach, the cost of remedial work may be considerably higher. Careful evaluation of each case is required by the client and engineer working together.

SUMMARY

TRL's research programme on expansive soils has been briefly described. The TRL research programme has:

(a)   shown that existing procedures for identifying expansive soils using index test data are frequently incorrect. An improved procedure has been developed.

(b)   shown by examination of existing information on suction beneath roads that many previous investigations have been poorly interpreted with regard to ground conditions. Extension of the early TRL work has led to a better understanding of the inter-relation between climatic and ground conditions in controlling the suction and moisture movement beneath roads. A low-cost field measurement probe using a filter paper sensor has been developed which is simple, robust and reliable. This is ideally suited for use in developing countries to obtain soil suction data beneath roads.

(c)   led to clarification of the influence of stress, density, suction and compaction moisture content on the swelling of expansive soils. Published procedures for swell testing have been compared experimentally. Recommendations have been made on appropriate test procedures.

(d)   identified the options available to road design engineers. Each of the options available have been described so that the design engineer can make a reasoned choice of which is appropriate for the project under consideration.

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GEOLOGICAL & GEOMORPHOLOGICAL ASSESSMENT

GEOLOGICAL & SOILS MAPS	GEOMORPHOLOGY	INSTRUMENTAL ANALYSIS
Bedrock geology may have a significant relationship to the type of soils developed. Valuable information on soil type and distribution can be gained if pedological maps are available for the area. Some maps showing local distribution of expansive soils may be available.	Presence of hummocky topography e.g. Gilgai. Surface drainage characteristics, e.g. Poor drainage favours formation of expansive soils.	Identify characteristic clay mineralogy e.g. X-ray diffraction, Differential thermal analysis, electron microscopy.

FIELD ASSESSMENT

FIELD DESCRIPTION & IDENTIFICATION	CONSISTENCY WITH RESPECT TO MOISTURE CONTENT	STRUCTURE	COLOUR	SUCTION	LOCAL KNOWLEDGE
Detailed soil profiling required.	High shear strength when dry. Soft and sticky when wet.	e.g. Shrinkage fissures and cracks Micro shattering giving granular appearance when dry. Highly polished slickensides.	May be of value on a regional or local level.	Expansive soils have a high suction towards water when partly dry.	e.g. Local authority engineers and builders may be a valuable source of information.

LABORATORY ASSESSMENT

LABORATORY IDENTIFICATION OF INTRINSIC EXPANSIVENESS

Determine plastic (w_p) and liquid (w_L) limits (BS 1377, part 2, 1990) & Shrinkage limit (w_s)(ASTM D4943-89 1992))

The proposed method of estimating intrinsic expansiveness uses the liquid limit (w_L) and the difference between the plastic limit and the shrinkage limit ($w_p - w_s$)

The lines on the graph represent expansiveness, (%), determined under a controlled set of conditions, as $(e_{15} - e_{SL})/(1 + e_{SL})$, where e_{15} is the void ratio after swelling under 15kPa vertical stress, of reconstituted, consolidated and dried samples. e_{SL} is the void ratio at the shrinkage limit.

This graph serves to provide comparative data for soils but does not provide a means of estimating expansiveness for any other conditions.
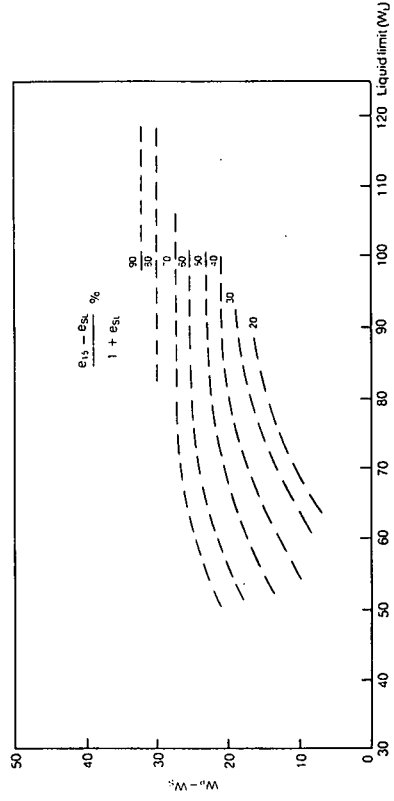

Table 1 Assessment of the expansiveness of soils.

TEST TYPE	NOTES ON TEST PROCEDURES	RECOMMENDATIONS
INDEX TESTS		
Atterberg limits (BS 1377, part 2 1990) (see 1) Shrinkage limit (ASTM D4943-89 1992) (see 2) Clay content (BS 1377, part 2 1990) (see 2) Linear shrinkage (BS 1377, part 2 1990) (see 2) Organic content (BS 1377, part 3, 1990) (see 2,3)	Used for identification of soil type. Preparation procedures may influence test results. Use only as a reference for qualitative assessment of expansiveness.	1. Test on fully remoulded sample and correct for whole soil. Reference test. 2. Express as a percentage of the whole soil. 3. Test from field moisture content.
Particle size distribution (BS 1377, part 2 1990)	Aggregations may be present.	Use wet sieving and hydrometer analysis with a suitable dispersant.
Salt Content	Salt content can affect solute suction and hence swell.	Flush sample and determine salt content and type in effluent.
VOLUME CHANGE INDICATOR TESTS		
e.g.Collapse Potential (Jennings & Knight 1975) Swell Potential Swell Pressure (Justo et al 1984)	Used only for investigation of possible volume change of unsaturated soils on wetting.	Careful interpretation of these tests is required. These are simple indicator tests and as such should not be used for design. They provide limited data under specific test conditions. Conflicting results can be obtained from swell potential and collapse potential tests on the same soil. Swell pressure is not related to the expansiveness of the soil.
QUANTITATIVE VOLUME CHANGE TESTS		
Swell followed by consolidation Type 'A' (Jennings et al 1973) Swell under load Type 'B' (Holtz & Gibbs 1956)	Type 'A' Appropriate where the pre-wetting or ponding technique is used in the field. Type 'B' This test can follow the loading and wetting sequence for most highway engineering projects. Can model the effect of water entry after construction.	It is important to match, as far as possible, the sequence of wetting (suction) and loading that will occur in the field. At early SI stage, before final designs are known. use Type 'B' at 10kPa and 50kPa vertical applied stress. This provides information for additional testing to permit final design to be done.
STRENGTH TESTS		
Triaxial Compression Shear Box	Determine effective cohesion and effective friction angle or strength under a particular set of conditions.	Due to low permeability, careful testing is required to allow dissipation or equalisation of pore water pressures.
Soaked CBR	Complete soaking may not be attained after 4 days.	Establish the effect of soaking by testing at 2, 4 and 8 days.
FIELD TESTS	Measurement of heave and associated suction change on appropriate test sites may be valuable.	Establish a profile of heave at depth with corresponding measurement of moisture content and suction. Fixed measuring points are required at the surface and to depth to determine heave. Moisture content can be determined using a suitable system such as nuclear methods. Suction can be evaluated using the TRL suction probe.

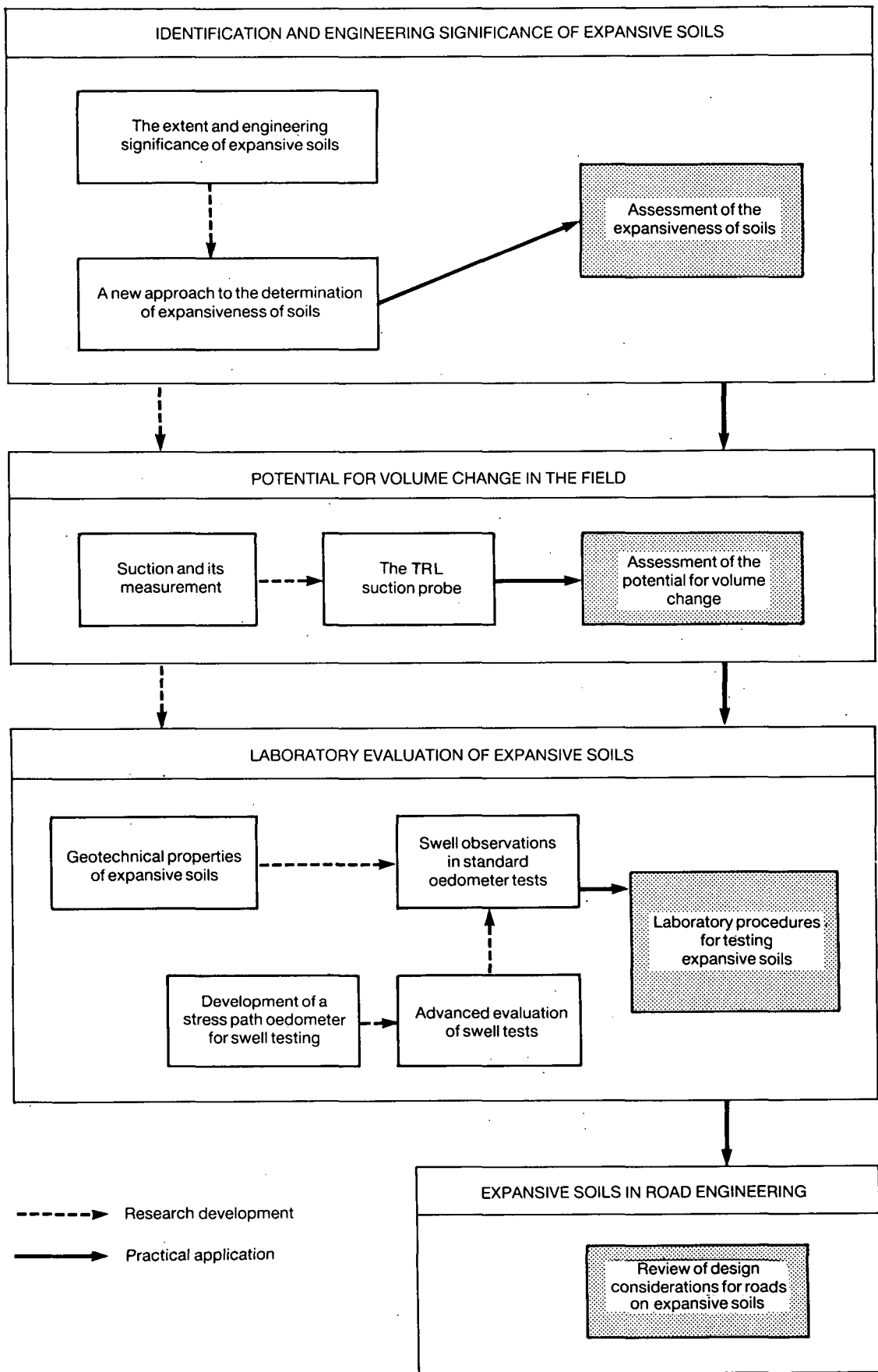Table 2 Some notes on procedures for evaluating expansive soils

Fig. 1 TRL's expansive soil research strategy

pF at 45cm depth
below centre-line
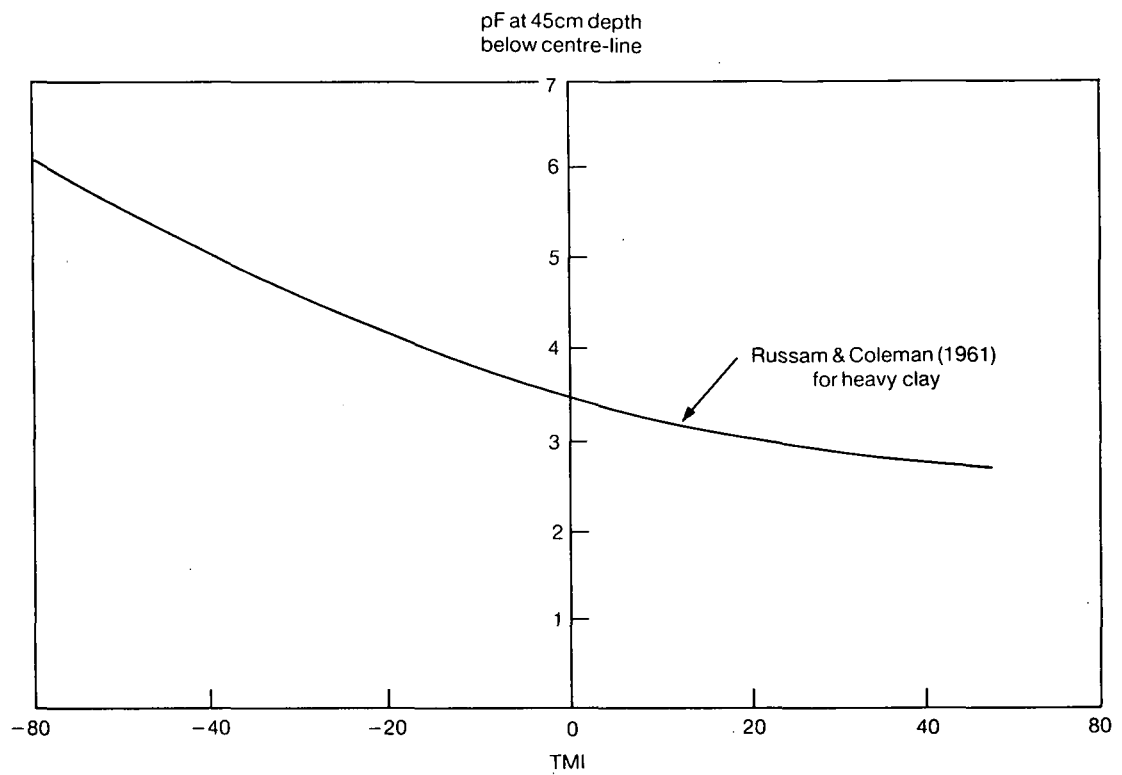
Russam & Coleman (1961)
for heavy clay

TMI

Fig. 2 The relation between soil suction and Thornthwaite Moisture Index for a heavy clay
used in the subgrade beneath the centre-line of a sealed road